"Applying High Resolution Imagery to Understand the Role of Dynamics in the Diminishing Arctic Sea Ice Cover"

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LONG-TERM GOALS

The proposed research aims to derive geophysical information and process understanding from declassified, high-resolution visible band satellite imagery. We will assess the available satellite imagery and extract parameters, including lead and ridge characteristics, that describe the state of the sea ice pack during of the last decade. Assessment of the satellite imagery database will help to improve our understanding of the physical environment of the Arctic Ocean, and the processes that define it.

OBJECTIVES

Our goal is to assess changes in the characteristics of the Arctic sea ice pack, during the last decade, in terms of (i) lead and ridge deformation features, (ii) ice type, (iii) ice thickness and (iv) ice strength,

establishing linkages to the yearly sea ice minimum extent. We will compare the rates of change in the seasonal ice pack in the Beaufort and Chukchi Seas with the multi-year ice of the Canada Basin and high Arctic (North Pole region).

The specific objectives are:

- To obtain, process and carefully assess the declassified, high-resolution visible-band imagery that is available from the Global Fiducials Library (GFL) at the U.S. Geological Survey (USGS), as described by *Kwok and Untersteiner* (2011) and *Kwok* (2014).
- To scale-up our analyses by incorporating additional data from IceBridge (airborne imagery and laser altimetry), ICESat and CryoSat-2 (satellite altimetry) that describe contemporary ice pack thickness, MODIS, AVHRR, RadarSat-2 (satellite imagery) that describe ice pack deformation features on large scales, as well as other relevant, publicly available data.
- To describe the role of sea ice dynamics in the transition of the Arctic ice pack from a predominantly multi-year ice pack to a seasonal cover. The combined data products will form a new database of geophysical parameters that describe the present-day Arctic ice cover, enabling the improvement of models used to forecast ice drift.

APPROACH

Our research is centered on the application of declassified, high-resolution visible band imagery that is available from the Global Fiducials Library (GFL) at the U.S. Geological Survey (USGS) (http://gfl.usgs.gov/ArcticSeaIce.shtml), for improved understanding of the nature of the Arctic ice pack. We will process and interpret the GFL imagery and combine the results with complementary products derived from high-resolution airborne digital imagery (from NASA's Operation IceBridge mission), satellite swath imagery, ice thickness from satellite and airborne altimetry (ICESat, CryoSat-2, IceBridge), and GPS ice drifters, to understand the dynamic signature of change over the last decade, particularly in the Beaufort/Chukchi Seas region. We will assess changes in sea ice mechanical properties (type, thickness, concentration, volume) and dynamics (lead, ice floe and ridge characteristics, ice drift).

We will test the hypothesis that sea ice in the Beaufort and Chukchi Seas is currently being preconditioned for future loss through changes to sea ice dynamics, in a way that irreversibly impacts the recoverability of the Arctic pack ice. In particular, we anticipate that lead spacing has decreased and lead width increased over the last decade in response to increased ice drift and deformation in the Beaufort/Chukchi Seas region. As a result, sea ice conditions in this region can negatively impact replenishment of multi-year ice across the entire Arctic, and a thinner pack, with increased lead fraction, will enhance the seasonal marginal ice zone formation and albedo feedback in summer.

WORK COMPLETED

We have conducted an assessment of the declassified, high-resolution visible-band images of the Arctic ice pack that are available at the GFL, USGS. The statistics related to the available images are reported in Table 1. During the reporting year we developed a new algorithm to classify imagery over both first-year and multi-year sea ice, identifying the following features: sea ice floes, thin ice, open water leads, pressure ridges and pressure-ridge shadows (Figures 1 and 2). We have processed and

interpreted the available GFL imagery acquired over the winter-time sea ice pack and have extracted statistics on lead distributions, floe size, surface deformation, and ridge height. We have also assessed the full archive of AVHRR data available for the Beaufort/Chukchi Sea region and have extracted the dates of lead formation related to specific shear patterns in the Beaufort Sea ice pack.

We are also leveraging observations collected by the NASA Operation IceBridge (OIB) project, including high-resolution visible-band imagery (*Onana et al.*, 2013), snow depth (*Newman et al.*, 2014), and sea ice thickness measurements (*Richter-Menge and Farrell*, 2013) acquired along IceBridge flight lines in the Western Arctic over a sever year period between 2009-present. Environment Canada (EC) has furnished the UMD team with RadarSat-2 imagery in the Western Arctic during Spring IceBridge campaign periods, under a special licensing agreement between NASA OIB and EC. We intend to incorporate results derived from these unique OIB data with the GFL declassified imagery to assess the changing characteristics of the seasonal ice pack in the Beaufort and Chukchi Seas and the multi-year ice of the Canada Basin and central Arctic.

During the reporting year undergraduate students Ms. Kate Faber, Mr. Ryon Merrick and Mr. Ben Lewis joined the project team at Oregon State University working under the guidance of Co-PI Hutchings. Mr. Kyle Duncan joined the University of Maryland team as a Faculty Research Assistant, working under the guidance of Co-PI Farrell. Ms. Faber is responsible for analysis of MODIS imagery and IceWatch data in the study region, Mr. Merrick is responsible for analysis of ice mass balance data in the study region, while Mr. Lewis is responsible for quantifying specific lead types and shear patterns in the Beaufort Sea, utilizing AVHRR imagery. Mr. Duncan is responsible for processing, analyzing, and interpreting the GFL and IceBridge remote sensing imagery datasets for the extraction of geophysical products and statistics to characterize the sea ice cover within the study region, particularly sea ice leads and surface deformation features.

Table 1: Summary of high-resolution NTM satellite images acquired over the Arctic sea ice pack that are currently available at the USGS Global Fiducials Library (GFL) database.

	The Beaufort/Chukchi Seas					**The High Arctic/Canadian Arctic**					
Winter[3]	Chukchi Sea	Beaufort Sea	Barrow	Sea Ice Buoys[1]	**Total**	Canadian Sea	Fram Strait	Sea Ice Buoys[2]	OIB North	OIB South	**Total**
1999-2003	0	0	0	0	**0**	0	0	0	0	0	**0**
2003-2009	0	0	0	0	**0**	0	0	0	0	0	**0**
2009-2014	7	10	14	22	**53 (15)**[5]	11	10	18	20	26	**85 (27)**[5]
Summer[4]											
1999-2003	0	87	0	0	**87**	84	84	0	0	0	**168**
2003-2009	34	30	31	32	**127**	32	29	82	0	0	**143**
2009-2014	39	36	52	320	**447**	58	53	371	41	42	**565**

[1] Buoy IDs: 31220, 586420, 732080, 17080, 772020, 956630, 132070, 48536, 824000, 86974, 92710, 123530, 128510, 240990, 252800, 216540; [2] Buoy IDs: 89179, 48534, 735060, 78227, 711760, 63541, 89188, 42597, 100013, 711490, 47611, 424080, 409520, 819920, 125530, 247800, 370080, 244420, 375030, 835100; [3] winter spans October – April; [4] summer spans May – September. [5] Number of images that are cloudy or dark.

Work Plan Status (Years 1 and 2):

- Obtain, process and interpret available high-resolution NTM satellite imagery from USGS GFL; extract lead width, frequency, distribution, floe size and ice concentration. [*ongoing*]
- Obtain, process and interpret available high-resolution airborne (DMS) imagery from the NASA IceBridge mission to extract lead width, frequency, distribution and floe size. [*ongoing*]
- Assess lead characteristics, contrasting results for seasonal and multi-year ice areas [*ongoing*].
- Collate mappings and trend analyses of related remote-sensing data sets including ice thickness, concentration, ice-pack drift, divergence and shear. [*completed*]
- Combine airborne (DMS) imagery with coincident high-resolution laser altimetry measurements of sea ice topography gathered by the NASA IceBridge mission to extract sea ice pressure ridge characteristics including ridge height, frequency, and distribution. [*ongoing*]
- Assess feasibility and develop novel techniques to extract ridge frequency and distribution statistics from GFL imagery [*underway*], incorporating satellite imagery at onset of summer melt [*in prep*.]
- Assess ridge characteristics, contrasting results for seasonal and multi-year ice areas. [*underway*]
- Define the overall deformation patterns of seasonal and multi-year sea ice packs by combining results from Years 1 and 2 on lead and ridge characteristics. [*underway*]
- Present results for presentation at national/international conferences. [*ongoing*]
- Prepare results for submission to peer-reviewed journals. [*underway*]

RESULTS

We have processed and interpreted 138 high-resolution GFL/NTM images of the winter-time sea ice pack to extract details on leads, newly-refrozen sea ice, floe size, surface deformation, and ridge height. Of these we found that 42 images were either dark or impacted by clouds and require further processing to extract segments of useful imagery, while 96 images were cloud-free and could be used for further interpretation of geophysical parameters (Table 1). Shadows cast by sea ice pressure ridges can potentially be mistaken for leads in the GFL/NTM imagery due to similarities in pixel intensity between features. Thus images containing pressure ridge shadows were also identified before extraction of lead and ridge statistics could be completed (Table 2). Table 2 shows that in the Beaufort/Chukchi Seas region 40 % of the images contain significant shadows cast by pressure ridges, while 60 % of the images were not impacted. In the high Arctic and northern Canada Basin we found that 35 % of the images were impacted by pressure ridge shadows, 43 % of the images were not impacted, and 22 % of the images were acquired over consolidated sea ice containing no lead features.

Table 2: Summary of images acquired over Arctic sea ice pack in winter that are impacted by ridge shadows.

Ridge Shadows?	The Beaufort/Chukchi Seas					High Arctic/Canadian Arctic					
	Chukchi Sea	Beaufort Sea	Barrow	Sea Ice Buoys	**Total**	Canadian Sea	Fram Strait	Sea Ice Buoys	OIB North	OIB South	**Total**
No	2	7	2	12	**23**	2	1	9	7	6	**25**
Yes	3	1	8	3	**15**	4	6	2	4	4	**20**
Floe Only[6]	0	0	0	0	**0**	0	0	0	7	6	**13**

[6] Images with no leads detected (no open water or thin ice)

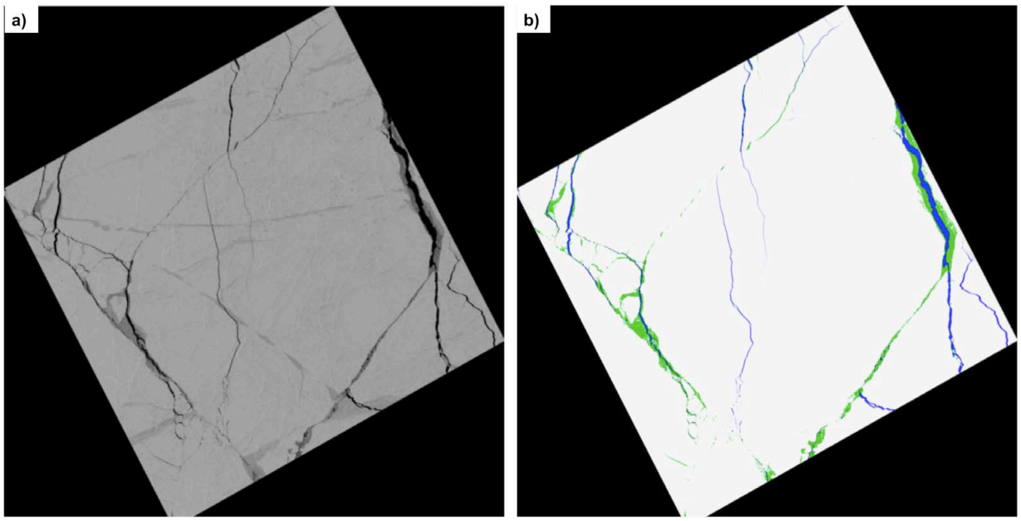

Figure 1: Example of the automated algorithm to identify thin ice and open water leads in the winter GFL/NTM imagery.
(a) Raw, high-resolution GFL/NTM image of first-year sea ice in the Beaufort Sea, acquired on 29th April, 2011. (b) Classification of thin ice types (green), open water leads (blue) and consolidated ice floes (white).

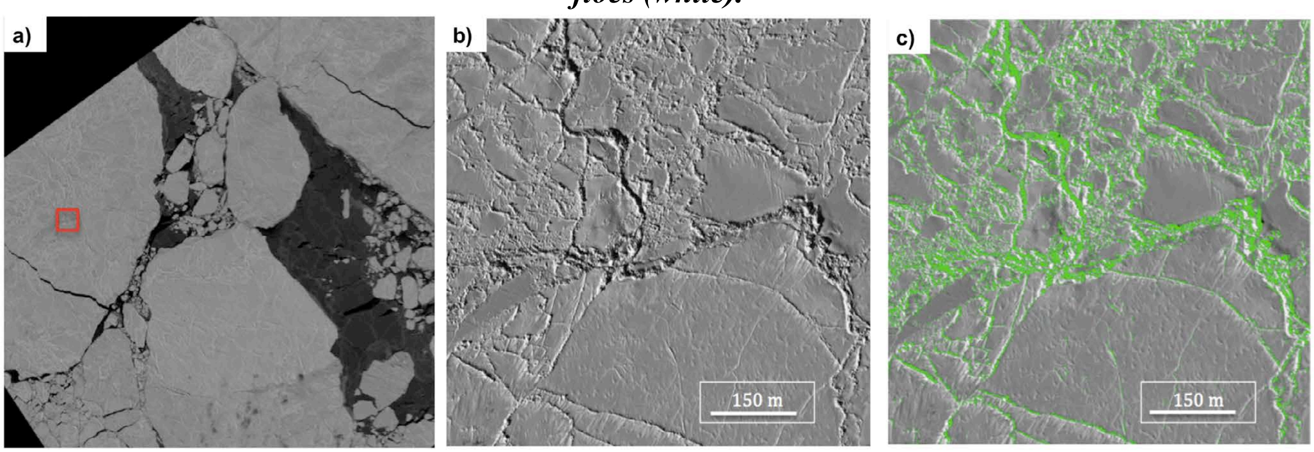

Figure 2: An example of automated algorithm to identify shadows cast by sea ice pressure ridges in the GFL/NTM imagery. (a) Raw, high-resolution GFL/NTM image of deformed sea ice in the Chukchi Sea, acquired on 14th April, 2012. (b) Details of sea ice morphology and deformation in area defined by red box in (a). (c) Classification of sea ice pressure ridges (white) and ridge shadows (green).

In tandem with our ongoing processing and assessment of GFL/NTM, AVHRR and IceBridge imagery for the extraction of sea ice geophysical parameters, we continue numerous, complementary investigations of the changing sea ice state in the Beaufort/Chukchi Seas (BC) region under related projects, assessing sea ice thickness (*Farrell et al.*, 2014; *Farrell et al.*, 2015; *Hutchings et al.*, 2015; *Richter-Menge and Farrell*, 2014), snow depth (*Newman et al.*, 2014; *Webster et al.*, 2014), sea ice deformation and drift speed (*Martini et al.*, 2015; *Petty et al.*, 2014; *Petty et al.*, 2015), dynamic forcing (*Arntsen et al*., 2015; *Hutchings et al*., 2014; *Kohout et al*., 2015; *Lukovich et al*., 2015) and thermodynamic forcing (*Carmack et al*., 2015; *Hutchings and Perovich*, 2015; *Perovich and Richter-Menge*, 2015; *Webster et al*., 2015).

In particular, we conducted a multi-decadal assessment of sea ice drift curl and wind curl in the BC region, spanning 1980 to 2013, utilizing NCEP-R2, ERA-Interim and JRA-55 reanalysis products together with an ice drift product derived from the Polar Pathfinder data available at NSIDC. Figure 3 shows that while there has been a strong trend in the anticyclonic ice drift curl over the 35-year period, there has been no significant trend in wind curl. These results demonstrate an amplified response of ice circulation in the BC region to wind forcing, especially during the late 2000s.

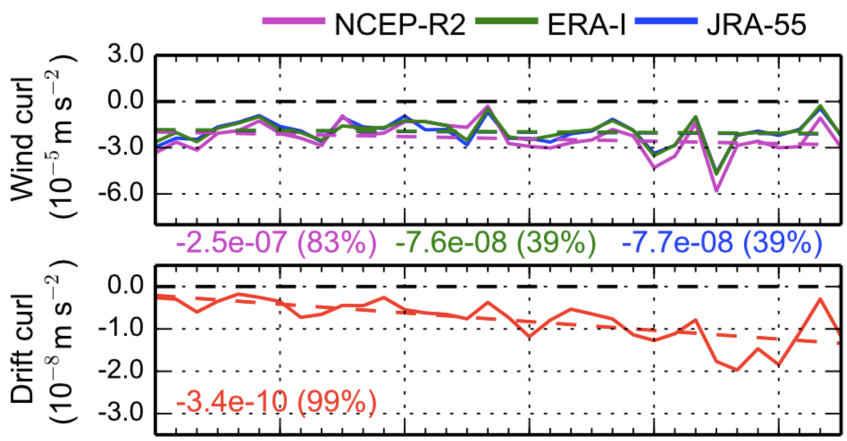

Figure 3: Annual mean 1980-2013 wind curl from ERA-I/NCEP-R2/JRA-55 reanalyses (top panel), ice drift curl from the NSIDC Polar Pathfinder product (bottom panel) in the BC region. The numbers between the top and bottom panel indicate the linear wind curl trends (and significance) for the three reanalyses data products. Red text shows linear drift curl trend (and significance). From Petty et al., 2015 (under review).

IMPACT/APPLICATIONS

The project will result in the assessment of the utility of declassified, high-resolution visible band imagery for deriving geophysical information on the sea ice pack of the Arctic Ocean, and improve understanding of key processes driving change in the region. Much of the geophysical understanding that underpins the parameterizations in current sea ice models describes a thick, multi-year ice pack. The metrics derived under this project describe the contemporaneous sea ice mechanical response to forcing, in both the seasonal and multi-year ice packs. This will facilitate improvement of ice drift in models, including refinement of sea ice rheology required for improved ice drift forecasting, and will inform the next generation of high-resolution sea ice models.

RELATED PROJECTS

- **ONR**: Richter-Menge is funded under a separate ONR project that utilizes the high-resolution satellite imagery to track the evolution of sea ice floes in the Arctic. Working together with D. Perovich the project, entitled "*The Seasonal Evolution of Sea Ice Floe Size Distribution*", will determine the evolution of floe size distribution and examine the role of winter preconditioning (i.e. refrozen cracks and leads) on summer floe breakup. Hutchings is collaborating with A. Mahoney, H. Eicken and C. Haas on an ONR-funded project "*Mass balance of multi-year sea ice in the southern Beaufort Sea*". This effort integrates in-situ, moored and aerial observations of ice thickness with sea ice drift from buoys and passive microwave to estimate the changing seasonality of ice thickness in the context of increasing multi-year ice melt in recent summers.
- **NASA IceBridge & ICESat-2**: The NASA IceBridge project is closely related to this ONR work. The goal of IceBridge is to utilize a highly specialized fleet of instrumented research aircraft to characterize annual changes in the thickness of sea ice, glaciers, and ice sheets. These observations are critical for predicting the response of Earth's polar ice to climate change and sea-level rise. IceBridge will also bridge the gap in observations between NASA's ICESat satellite missions. Farrell and Richter-Menge currently serve as members of the IceBridge Science Team and can thus facilitate coordination of future IceBridge flights over specific sea ice targets where spatially and temporally coincident high-resolution satellite imagery may be obtained. Farrell is also a member of the NASA ICESat-2 Science Definition Team.
- **NASA**: Research project entitled "Sea Ice Dynamics and its Role in Understanding the Survivability of Arctic Sea Ice", funded through the NASA ROSES 2012 Cryospheric Science Program, aims to quantify how sea ice in the Beaufort-Chukchi Seas (BC) region has changed, and to understand the role of sea ice dynamics as a driving force for transformation in this area. The study will define the changes that have occurred in the BC region during the last decade, based on analysis of the following geophysical parameters: ice type, ice thickness distribution, ice age, ice volume transport and drift, melt and freeze onset dates.

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